Final Report for NASA Grant NAG5-5209:
Ultra-long Duration Balloon Mission Concept Study:
***EXIST-LITE* Hard X-ray Imaging Survey**
(October 1, 1998 - September 30, 2001)

1 Introduction and Overview

We carried out a mission concept Study for a ULDB mission to conduct a high-sensitivity hard x-ray (~20-600 keV) imaging sky survey. The EXIST-LITE concept has been developed, and critical detector technologies for realistic fabrication of very large area Cd-Zn-Te imaging detector arrays are now much better understood. A ULDB mission such as EXIST-LITE is now even more attractive as a testbed for the full EXIST mission, recommended by the Decadal Survey, and now included in the NASA Roadmap and Strategic Plan as one of the "Einstein Probes".

In this (overdue!) Final Report we provide a brief update for the science opportunities possible with a ULDB mission such as EXIST-LITE and relate these to upcoming missions (INTEGRAL and Swift) as well as the ultimate very high sensitivity sky survey mission EXIST. We then review the progress made over this investigation in Detector/Telescope design concept, Gondola and Mission design concept, and Data Handling/Analysis.

2 Updated Science and Mission Opportunities

Since the original (June 1998) submission of our proposal for the EXIST-LITE study, the interest in conducting a deep hard x-ray (HX) survey has grown: as noted above, a deep survey mission such as EXIST is now included in the NASA Strategic Plan as the "Black Hole Finder Probe". This is because of the increasing recognition that the HX band (~10-600 keV) is crucial to address a number of key problems of current interest. The key science drivers for the full-scale EXIST mission (cf. Grindlay et al 2001, 2003) are significant when scaled for the pathfinder survey that could be carried out with EXIST-LITE.

2.1 EXIST-LITE Science Goals

As described in the next section on detector and telescope design, the EXIST-LITE mission could achieve survey exposures and sensitivities (for a 100d ULDB mission) even better than originally proposed. The revised sensitivity and exposure curves are shown in Figure 1 and are relevant for the updated Science Goals.

2.1.1 Imaging Surveys (Maps)

Obscured AGN survey: It is becoming increasingly clear that most of the accretion luminosity of the universe is due to obscured AGN, and that these objects are very likely the dominant sources for the cosmic x-ray (and HX) diffuse background (e.g. Fabian 1999). No sky survey has yet been carried out to measure the distribution of these objects in luminosity, redshift, and broad-band spectra in the HX band where, as became clear from BeppoSAX (e.g. Vignati et al 1999), they are brightest. The recent

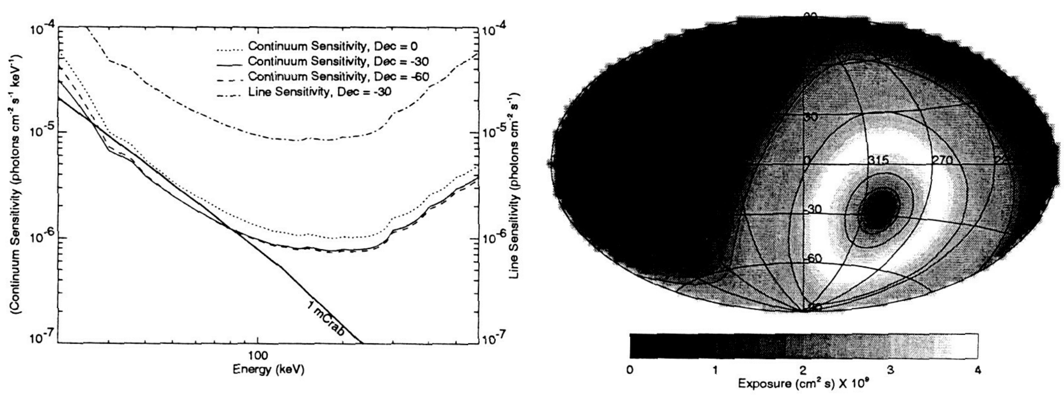

Figure 1: Sensitivity estimates (left) for 100d ULDB mission now including depth sensing and collimator shadowing. Exposure map (right), or Area $\times$ time, for 100d southern hemisphere flight with collimator corrections.

BeppoSAX surveys of Seyfert 2 AGN (e.g. Vignati et al 1999) have shown dramatically the effects of very large absorbing column densities (NH $\sim 10^{24}$cm^{-2}) in these objects, with the HX spectra rising sharply above $\sim$10 keV as shown in Figure 2.

A half-sky survey with 1mCrab sensitivity, such as possible with a southern hemisphere $\sim$100d ULDB flight of EXIST-LITE, could image and study some $\sim$50 of these for detailed followup study as a prelude to a deep survey with EXIST for much fainter objects. Such a survey would complement the HX survey conducted with Swift, with comparable ($\sim$1mCrab) sensitivity, by providing longer timescale coverage (daily observations of each source for 100d) than the separated $\sim$1-3d exposures for any given source likely to be obtained with Swift.

Black hole accretion on all scales: The study of black holes, from x-ray binaries to AGN, continues to be one of the most compelling goals. The HX band allows their ubiquitous Comptonizing coronae to be measured, and an un-biased survey can enable followup studies to measure dependences of coronal properties on fundamental BH properties (mass and $\dot{m}$). The relative contributions of non-thermal jets at high $\dot{m}$, most relevant for EXIST-LITE, requires broad band coverage to $\gtrsim$ 511 keV. HX spectral variations vs. broad-band flux can test the underlying similarities in accretion onto BHs in binaries vs. AGN.

Stellar black hole content of Galaxy: X-ray novae (XN) appear to be predominantly BH systems, so their unbiased detection and sub-arcmin locations, which allow optical/IR identifications, can provide a direct measure of the BH binary content (and XN recurrence time) of the Galaxy. XN containing neutron stars can be isolated by their usual bursting activity (thermonuclear flashes), and since they may solve the birth rate problem for millisecond pulsars (Yi and Grindlay 1998), their statistics must be established. A deep HX survey of the galactic plane can also measure the population of galactic BHs not in binaries, since they could be detected as highly cutoff hard sources projected onto giant molecular clouds. Compared to ISM accretion onto isolated NSs, for which a few candidates have been found, BHs should be higher luminosity and thus much more readily detectable due to their intrinsically harder spectra and (much) lower expected space velocities, V, and larger mass M (Bondi accretion depending on M^2/V^3).

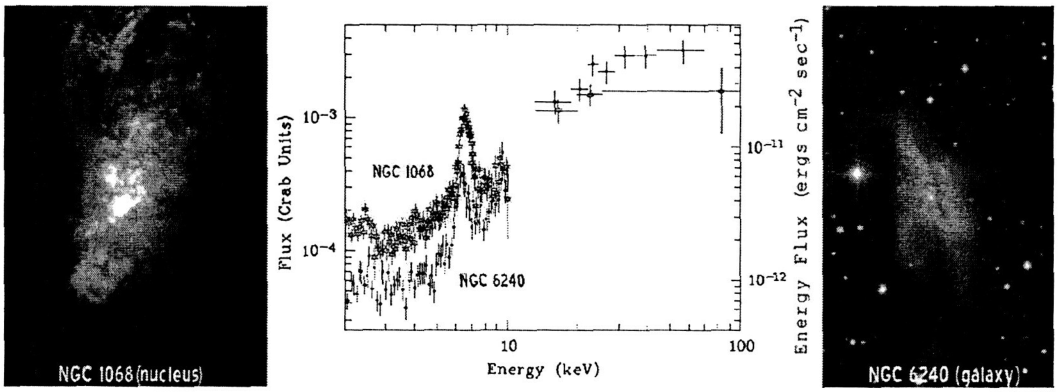

Figure 2: BeppoSAX spectra of the Seyfert 2 systems NGC 6240 and 1068 (Vignati et al 1999) showing the large low energy cutoffs in these dusty AGN for which images are shown left (HST) and right (ESO 2.2m).

Galactic survey for obscured SNR: SN rate in Galaxy: Type II SNe are expected to disperse $\sim10^{-4}$ $M_{\odot}$of ^{44}Ti, with the total a sensitive probe of the mass cut and NS formation. With a ~87y mean-life for decay into ^{44}Sc which produces narrow lines at 68 and 78 keV, obscured SNe can be detected throughout nearly half the Galaxy for ~300y given the ~2 x 10^{-5} photons cm^{-2} s^{-1} line sensitivity (cf. Fig. 1) and ~2 keV energy resolution (at 70 keV) possible for EXIST-LITE. Thus the likely detection of Cas A (Iyudin et al 1994) can be extended to more distant but similarly (or greater) obscured SN to constrain the SN rate in the Galaxy: if the galactic SN rate is ~3/century, then of the ~10 expected since Cas-A, perhaps 5 should be detected. The nearly half-sky imaging of EXIST-LITE would extend the central-radian galactic survey planned for INTEGRAL.

2.1.2 Temporal Surveys and Bursts

The wide field of the EXIST-LITE survey telescopes ensures they will have long continuous pointings, uninterrupted by 95min orbital occultations. Over a full 100d ULDB mission they will provide excellent temporal and all sky monitoring (ASM) science. The brightest AGN (e.g. Cen A) will be monitored for daily flux variations continuously over the full flight, providing the first long time-duration variability studies at hard x-ray energies.

Gamma-ray Bursts: The long-duration flight, and wide field of view (FoV), also enables detection of rare events such as gamma-ray bursts (GRBs) or soft gamma-ray repeaters (SGRs). The extension to higher energies (~600 keV) for EXIST-LITE than possible with Swift (~150 keV) would allow complementary studies of bursts. Given the comparable detector area and total FoV of EXIST-LITE and Swift, but factor of ~2 reduced sensitivity of EXIST-LITE due to residual atmospheric attenuation, over a 100d ULDB mission about 10 GRBs are expected. These could be followed up by Swift (which can respond to external triggers), if not already detected, and redshifts derived from the optical afterglow expected to be detected for at least half. The extended energy range of EXIST allows a measurement of "photometric redshift" from the ΔE - $\Delta\tau$ (energy-lag) relation of Norris et al (2000), allowing an important calibration of this relation for relatively faint bursts, and important to assess its utillity for the full EXIST mission.

Soft Gamma-ray Repeaters: population in Galaxy and Local Group: Only 3 SGR sources are known in the Galaxy and 1 in the LMC. Since a typical ~0.1sec SGR burst spike can be imaged (5σ) by EXIST-LITE for a peak flux of ~400 mCrab in the 20-60 keV band, the typical bursts from the most recently discovered SGR1627-41 (Woods et al 1999) with peak flux $\sim 2 \times 10^{-6}$ ergs cm^{-2} s^{-1} would be detected out to ~50 kpc. Hence the brightest "normal" SGR bursts are detectable out to ~0.8 Mpc and the rare giant outbursts (e.g. March 5, 1979 event) out to ~10 Mpc. Thus the population and physics of SGRs, and thus their association with magnetars and young SNR, can be studied in M31 and the rare super-outbursts thoughout the Local Group.

HX blazar alert and spectra: measuring diffuse IR background: The cosmic IR background (CIRB) over ~1-100μ is poorly measured (if at all) and yet can constrain galaxy formation and the luminosity evolution of the universe, complementing the obscured AGN survey. As reviewed by Catanese and Weekes (1999), observing spectral breaks (from $\gamma - \gamma$ absorption) for blazars in the band ~0.01-100 TeV can measure the CIRB out to z ~1 *if* the intrinsic spectrum is known. Since the γ-ray spectra of the detected (low z) blazars are well described by synchrotron-self Compton (SSC) models, for which the hard x-ray (~100keV) synchrotron peak is scattered to the TeV range, the HX spectra can provide both the required underlying spectra and time-dependent light curves for all objects (variable!) to be observed with GLAST and high-sensitivity ground-based TeV telescopes (e.g. VERITAS).

Accretion torques and X-ray pulsars: The success of BATSE as a HX monitor of bright accreting pulsars in the Galaxy (cf. Bildsten et al 1997), in which spin histories and accretion torques were derived for a significant sample, can be greatly extended with EXIST: the very much larger reservoir of Be systems can be explored, and wind vs. disk-fed accretion studied in detail. The wide-field HX imaging and monitoring capability will also allow a new survey for pulsars and AXPs in highly obscured regions of the disk, complementing the ^{44}Ti survey.

2.2 Relation to Other HX Survey Missions

If EXIST-LITE were flown as a ULDB mission in c. 2006, it could be highly complementary to INTEGRAL (still operating) by extending the central galactic radian survey planned for INTEGRAL to the entire Galaxy. The projected ~1mCrab sensitivity is ~10× more sensitive than the INTEGRAL galactic plane survey so that the ~100d ULDB mission could help guide the INTEGRAL galactic plane observing program for longer observations of fainter transients.

The hard x-ray sky survey expected for Swift would be comparable in sensitivity to EXIST-LITE but would differ in two key ways: the upper energy range (~150 keV vs. 600 keV) and the total exposure time and coverage. Swift will conduct its serendipitous Survey by accumulating exposure on any given source in (typically) ~1d integrations every ~6-10days given its 2sr FOV and the planned ~1d pointings planned to study afterglows from the GRB detected that day. The ~1d continuous pointings are of course typically earth-occulted (for a given source) for ~half the time. In contrast, EXIST-LITE observes a given source continuously for ~4-8hours each day throughout the entire mission (and a polar LDB flight – see below – would allow *continuous* viewing of a significant region of sky). Thus the sensitivity for source variability on both short (~3h) and intermediate (~3-10d) timescales is enhanced with EXIST-LITE (hence it is indeed a *L*ong *I*ntegration *T*ime *E*xperiment).

Finally, the ULDB mission would be the prudent precursor to a full EXIST mission, which could

EXIST-LITE Telescope/Gondola Concept

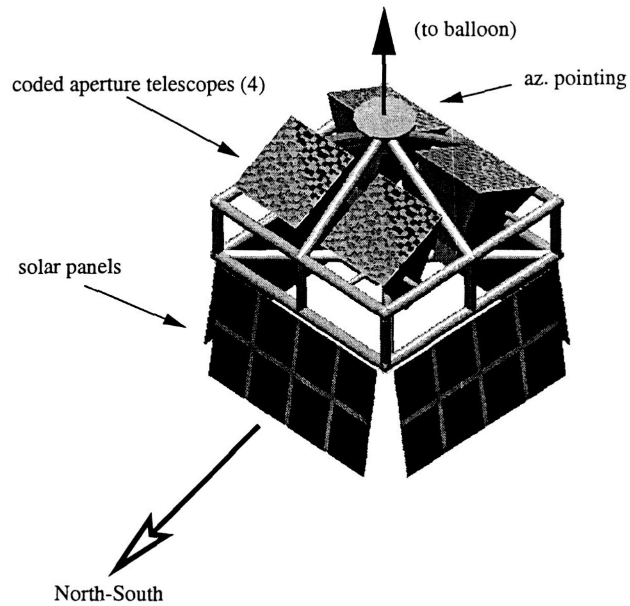

Figure 3: Overview of EXIST-LITE concept, showing 4 coded aperture telescopes in gondola. Each telescope includes a 1600cm^2 imaging CZT array mounted 1.5m below the coded aperture mask with a $40^\circ \times 40^\circ$ field of view. The two-telescope pairs are shown fixed-mounted at elevation offsets $\pm 20^\circ$ from the zenith; alternatively, the telescope pairs could be separately pointed in elevation also.

follow in c. 2010 if EXIST were selected as the first Einstein Probe mission. The EXIST mission would achieve the ultimate HX survey sensitivity, ~0.05mCrab, by incorporating a very large detector array area (8m^2). As now envisioned (see below), EXIST-LITE could fly the equivalent of (nearly) 2-4 of the sub-telescopes (9 per Telescope) in the current EXIST concept (Grindlay et al 2003). This would allow for realistic flight hardware development and testing on a mission that itself could yield cutting edge science.

3 EXIST-LITE Mission Concept

The mission concept has been refined over this Study and the detector/telescope and gondola systems further developed. Although the detector and gondola work has been primarily supported by our separate SR&T programs (to Harvard and MSFC), this ULDB study has been essential to developing the overall mission concept.

3.1 Overall Mission Concept: Telescope and Gondola Systems

The baseline mission concept is illustrated in Figure 3, where we show the fixed array of 4 coded aperture telescopes mounted in a relatively compact gondola.

The telescopes each have $40^\circ \times 40^\circ$ (FWHM) fields of view, $10'$ resolution, and are fixed at offsets

Table 1: EXITE-LITE Mission Characteristics

Energy Range	20-600 keV
Energy Resolution	2.5 keV FWHM @60 keV
Field of View	$40^\circ \times 80^\circ$
Angular Resolution	$12'$
Time Resolution	0.6 millisecond
Survey Sensitivity	~1mCrab (30-150 keV)
Number of Telescopes	4
Mask	URA ($\sim 256^2$) 4-7mm thick Tungsten
Focal Length	1.5 m
Detectors	CdZnTe (20mm× 20mm× 5mm crystals; 8× 8 pixels (2.5mm))
Total Detector Area and Pixel No.	6400 cm^2; 102,400 pixels
Collimator/Shield	1 cm/2 cm CsI, or Pb-Sn-Cu/plastic scint.
Total Payload (gondola and telescopes) mass	1100 kg
Power	350 W
Event Rate	$\sim 2000 - 4000\ sec^{-1}$
Data Rate	100-200 kbs (full); $\lesssim$ 100 kbs (compressed)
Command Uplink	1 kbs (~3×/day)

of $\pm 20^\circ$ from the gondola zenith in 2 pairs (alternatively, each telescope could be pointed separately in elevation). The combined $40^\circ \times 80^\circ$ FOV then would then be oriented north-south by the gondola pointing system. Sources drift-scan from East to West across the 40° dimension of the combined FoV with an exposure time ~4-8h, depending on the source DEC and balloon latitude. With each telescope focal plane instrumented with 1600cm^2 of pixellated Cd-Zn-Te (CZT) detectors at 1.5m behind the coded aperture mask(see below), the total Area × Time product for a 100d flight is that shown in Fig. 1. A summary of the EXIST-LITE mission characteristics is given in Table 1.

3.2 Detector Design and Prototypes

As a precursor to a full EXIST mission, EXIST-LITE would have CZT detector crystal arrays (DCAs) similar to that described in Grindlay et al (2003): 2 × 2 crystals (each 2cm × 2cm × 0.5cm) close-tiled onto a common carrier board with inter-crystal gaps of 0.5mm. For EXIST-LITE and its ~1mCrab survey sensitivity, it is only required to have $10'$ angular resolution to be (well) below the confusion limit imposed by the expected number of sources at high latitude (~50 AGN expected in full half-sky survey) or in the galactic plane (e.g. ~30-100 sources expected in the central 40° around the galactic center). Thus for the nominal 1.5m focal length of the coded aperture telescopes, the spatial resolution required on the CZT readout is 2.5mm to oversample the shadow of the 5mm pixel pitch of the coded aperture mask. The DCAs would be themselves close-tiled (1.2mm gaps) into 5 × 5 arrays to constitute a Detector Module (DM), each then containing 20cm × 20cm of close-packed CZT. A 2 × 2 array of such DMs, themselves close-tiled with the same (as DCA) 1.2mm gaps, forms the complete 40cm × 40cm focal plane of each of the 4 telescopes.

Under our separate (Harvard) SR&T program we have developed a laboratory prototype of a DCA and a small DM (2 × 2 array of DCAs). An image of the proto-DM is shown in Figure 4 together with a 60 keV shadow-graph image using a ^{241}Am source and occulting Pb mask with "H". The 4 crystals on each DCA, which together have 16 × 16 pixels (8 × 8 at 2.5mm pitch on each crystal) are readout by 2 × 128 channel ASICs (XAIM3.2; from IDEas Corp., Hoevik, Norway). Preliminary results with this DCA were reported in Narita et al (2000); more extensive testing of the full proto-DM as well as with a depth-sensing cathode readout is given by Hong et al (2003).

The CZT crystals to be used for EXIST-LITE (each 2cm × 2cm × 0.5cm) would likely be supplied by IMARAD Corp. (Rehovot, Israel) since we have found (Narita et al 1999) this CZT, grown by the horizontal Bridgman process, to be relatively free of 'cracks' or 'pipes' which are typically present in all but the highest quality crystals grown from more traditional high pressure Bridgman process (e.g. from eV Products). The

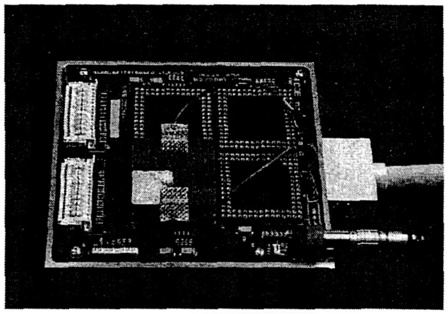 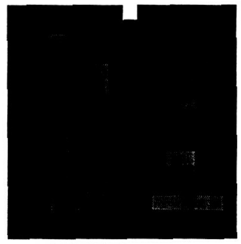

Figure 4: Left: Lab prototype tiled CZT array (4 DCAs; only lower left inserted) and Right: 60 keV image from one DCA.

metal contact employed by IMARAD in their commercial detector is In, which creates an ohmic type contact with significant leakage current in this CZT which we have found to have inherently lower bulk resistivity ($\sim 10^{10}$ ohm-cm) than CZT from eV Products. Motivated by our previous work with PIN contacts on eV Products CZT (Narita et al 1998), we experimented with blocking contacts (CdS and ZnTe) on the IMARAD material which increased the detector resistivity to about2 $\times$ 10^{10} ohm-cm, thus leading to an improved spectral resolution. The 4mm and 5mm thick IMARAD material detectors with blocking contacts were successfully biased up to 1500 volts and showed nearly complete depletion or field uniformity (Narita et al 1999). Results for detectors with Au/CdS and Au/In (cathode/anode pixels) were reported in Narita et al (1999). We also found that a simple gold electrode (rather than In, as employed by IMARAD) used on IMARAD material forms a Schottky contact which reduces the leakage current by a factor of $\gtrsim$ 15, comparable to a PIN detector (Narita et al 2000). We have also found that Pt (instead of Au) contacts on IMARAD CZT forms a much more reliable Schottky detector with similarly low leakage current (Jenkins et al 2003). These would likely be used for EXIST-LITE (and possibly EXIST).

Finally, we have performed two balloon flight tests (September 2000 and May 2001) of IMARAD vs. eV Products CZT crystals (1cm $\times$ 1cm $\times$ 0.5cm) tiled together in a mini-array (1 $\times$ 2) crystals, and shielded by a passive photon shield (Pb-Sn-Cu) enclosed by an active (plastic scintillator) particle shield. Each crystal had a 4 $\times$ 4 array of anode pixels and was "flip-chip" coupled (conductive epoxy-bonded) to a carrier board (proto-DCA) read out by a 32 channel VA-TA ASIC provided by IDE AS (Hoevik, Norway). The VA-TA is a self triggering ASIC design where all the channels are recorded and readout from a single channel trigger. In contrast, the ASIC used for the full proto-DM (Fig. 4) is a single-channel output (peak triggered pixel only). For EXIST-LITE, we would use a multi-pixel readout ASIC (peak plus neighbor pixels or pixels ordered by pulse height) to allow for Compton event detection. The balloon flight results obtained with the system shown in Fig. 5 were primarily to measure in-flight detector backgrounds. These were found to agree well with predicted values. Results are reported in Bloser et al (2002) and Jenkins et al (2003).

3.3 Telescope Design

We have considered the design and layout of the wide-field survey telescopes (see Fig. 3) to consider the effect of pixel size, corresponding detector size, occultation by the collimation effect of the coded mask, and collimator/shield design. These design tradeoffs are similar to those described for the full EXIST mission, as summarized in Grindlay et al (2003). Very briefly, the major factors are:

- For a hard x-ray survey, the field of view, θ, should be as large as feasible without introducing significant compromises in imaging due to autocollimation of the mask holes or compromising depth-dependent projection (onto the focal plane) accuracy for image reconstruction. Increased FoV, and thus diffuse flux background, B, (typically only dominant at energies /la100 keV), is offset by increased exposure

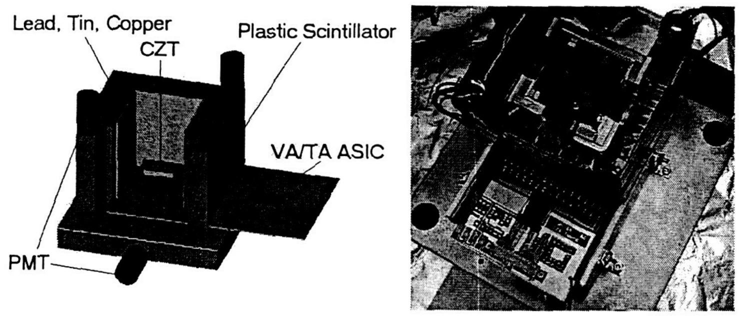

Figure 5: Flight prototype tiled CZT array (2 detectors) and ASIC readout with shield/collimator. Left: conceptual layout, and Right: actual flight hardware.

time, T, on any given source for a scanning experiment with fixed scan rate (i.e. the drift scan rate for EXIST-LITE). Since sensitivity is $\propto (T/B)^{0.5}$, a larger FoV survey telescope is achieves the same limiting sensitivity but at the same time allows longer exposure time on any given source for enhance time variability studies.

- The imaging resolution $\delta theta$ should be fine enough that source confusion is not worse than the standard criterion of $\sim$1 source per 40 "beam" widths. For EXIST-LITE, this is determined by the expected source crowding in the galactic bulge and not at high latitudes (as for EXIST). With $\sim$30 sources expected (from HEAO-1 source catalogs) within 20° of the galactic center, this gives a requirement for $\sim 10'$ resolution.
- The coded aperture mask thickness must be sufficient to attenuate photons at the desired high energy limit of the imager to a nominal factor (e.g. 1/e). For 600 keV, the thickness for a tungsten mask must be 6mm to achieve 1/e transmission. For the desired angular resolution ($10'$) and desired coded aperture telescope focal length (1.5m; to keep the overall telescope structure compact and thus coded aperture mass a minimum), the required coded mask pixel size (5mm) ensures that isolated single mask pixel holes will be no more collimating than the 40° (FWHM) imposed by the collimator below the mask. That is, the collimation of a single pixel defines an autocollimation FoV with FWHM $\theta = \tan^{-1}(5/6) \sim 40°$. The coded aperture mask for each telescope must have dimension 1.5m $\times$ 1.5m to extend out to the 20° (HWHM) angle beyond each edge of the 40cm detector plane. With 6mm thickness, each coded aperture (half-filled with holes) thus has total mass 128kg.
- The collimation to ensure the CZT detector plane sees the desired FoV is imposed by a mechanical collimator above the detector plane. It cannot be imposed by the autocollimation of the mask pixels alone since $\sim$half of the mask pixels are not isolated (single open mask holes) and thus the effective autocollimation is reduced by larger effective open pixel size (of adjacent open mask pixels). The mechanical collimator planned for EXIST-LITE would be a combined passive photon shield (6mmPb-1mmSn-0.5mmCu) and plastic scintillator (1cm) particle anti-co shield or a single 1cm thick CsI photon-particle shield on all 4 sides of each telescope. The collimator shield is 48cm high on all 4 sides to achieve the 40° FWHM across the 40cm detector, and its thickness tapers to 0.7 of its base value at the top to allow for projected path length effects. Possibly, the collimator would be active only for its lower $\sim$2/3 and passive for the upper portion only where photons produced in the collimator by either particle or photon events have a relatively small probability of striking the detector plane below. The total mass of a passive (only) collimator would be 48kg for each telescope vs. 28kg if entirely CsI.
- The telescope must be shielded from the rear to minimize detector background with shielding of approximately 2cm CsI for both photon and particle rejection. This would add an additional mass of 15kg to each telescope.

The total mass of the coded mask, collimator and shielding (assuming CsI) for each telescope is thus 171kg. Combined with CZT and DCA mass (9kg), supporting aluminum and carbon fiber structure (20kg), and electronics (10kg), the total mass of each telescope is approximately 210kg. This could be reduced by nearly half if the high energy limit was reduced from 600 keV to 300 keV, with correspondingly lower thickness of the mask and shields and thus mass.

3.4 Gondola Design and Prototype

The gondola required for EXIST-LITE (cf. Fig. 3) is relatively compact cubic open frame braced aluminum (or carbon fiber) tube structure (approximately 2.8m × 2.8m × 2.8m) and requires only a relatively crude azimuth pointing system. Pointing is north-south, and need only be maintained to coarse accuracy: absolute pointing (N-S) is required to only ($\sim 1°$), given the large ($40°$) FoV. However pointing stability should be better so that drifts in absolute pointing direction are at a rate $\lesssim 0.5\times$ the rate at which guide stars (or a source) drift across the FoV. Given the maximum drift rate (for a source with DEC = $0°$) of $15''$/sec, this implies a pointing stability of $\sim 5''$/sec or $5'$ /min.

Given that the pointing-aspect system would be gyro and star-camera based (though a simple GPS-only option is also possible; see below), the gondola could conduct inertial pointing, rather than normal fixed north-south pointing to conduct its drift scan sky survey, for observations of selected targets (e.g. transients or sources of special interest) during the flight. This could be conducted from ground command or be pre-programmed (e.g. 1hour inertial pointings on the galactic center as it transits each day; or 10min pointings on the Crab each day for absolute calibration). Inertial pointing would not necessarily require an elevation drive for the telescopes (as shown in Fig. 3, they could be fixed at elevations $\pm 20°$ from the zenith) since inertial tracking in azimuth only would keep the source drifting at a slower rate in elevation only and simplify telescope mounting and gondola systems. This would be studied in a final design for ULDB implementation.

3.4.1 Pointing System

A flight-proven pointing system design would be based on systems developed at MSFC (for our joint Harvard-MSFC flight in May 2001) and LLNL (for an upcoming Caltech-LLNL flight of HEFT) to incorporate the autonomous systems needed for ULDB operation.

Pointing control of the gondola can be broken into two operational modes; Rough control which is primarily positional and fine control which is primarily rate. The primary rough azimuth sensor is a 4-antenna GPS-based attitude determination system made by Trimble navigation with an update rate of 10Hz and an accuracy approaching $0.1°$ RMS. Rough elevation control is provided by measuring the elevation angle of the detectors relative to the structure using a 16 bit shaft angle encoder. Deflection of the gondola structure from gravity gradient is measured by an inclinometer mounted parallel to the line of sight. The inclinometer accuracy is approximately $2'$ RMS. Factoring in these and other effects such as misalignments between the fixed gondola structure and instrument's pointing axis, we conservatively expect the pointing accuracy of the rough system to be within a $15'$ radius of the desired target position.

Once a target is within the rough pointing window the system switches to fine control using the aspect camera system as the primary azimuth and elevation error sensor and rate gyros as the primary control loop variable. These gyros have a short term resolution of 0.1 earth rate or $\sim 4\times 10^{-4}$ deg/sec when operated at a bandwidth of 0.5 Hz. Long term drift is unimportant as camera updates will provide corrections within a maximum 10 s period during which gyro drift is acceptably small. After a star field is identified the aspect system will calculate a correction rate based on the pointing error and transmit this to the control system to be used as a new control setpoint. Guide star RA/DEC coordinates and star fields are stored before launch (but can be updated in flight).

3.4.2 Aspect Camera

Aspect requirements are set by having to measure guide stars drifting across the star tracker at the drift rate. A daytime startracker has been designed by our MSFC colleagues and successfully flown on our combined May 2001 Harvard-MSFC balloon flight in which the first daytime star images (down to 8th mag) were obtained within a 2.8° FoV (Dietz et al 2002). The system flown is based on a SenSys digital star camera configured with a Kodak 1401e CCD. This chip has a 1340 × 1037 array of 6.8 μm square pixels and features high quantum efficiency, especially in the red portion of the spectrum. The camera views the sky though an F2.8, 64.3-mm-diameter Zeiss lens, giving a total field of view of 2.8° × 2.2°, or approximately 7.8 × 7.8$''^2$ per pixel. This small pixel solid angle enables stars to be seen even against the daytime sky at float altitudes. Simulations with the Air Force Geophysics Laboratory's MODTRAN atmospheric model, coupled with data on star counts as a function of limiting magnitudes for various wavelength bands, have shown that by working in the red region (600-800 nm)around 8^{th} magnitude sensitivity can be achieved in a $\sim$1 s exposure at 35 km altitude. This is enough to ensure several resolvable stars in the field of view even at high galactic lattitudes where the star density is low. To reduce scattered radiation, particularly from the balloon, the camera system is heavily baffled. A 9-stage, 3-m-long baffle, enures an attenuation of greater than 10^{-7} at all angles beyond 5° off axis. For EXIST-LITE, with its wide FoV, the star camera can be aligned with the "lower" elevation side of the FoV thus keeping it farther from the bright balloon overhead and thus allowing the baffle length to be shortened to (probably) $\lesssim$ 2m. This also has the advantage that for a southern hemisphere ULDB (or LDB) flight, the camera is viewing sky closer to the celestial pole so that the star drift rate is correspondingly reduced from the equatorial rates given above.

Pattern recognition software, which can quickly locate bright stars and determine offsets from desired pointing directions, was developed and tested successfully on the May 2001 flight. The overhead for this procedure is less than 0.5 s for the on-board control-system computer. For certain high-sky-background pointing directions, where the CCD wells may fill in less than 1 s, it may be necessary to add up to 3 frames to achieve the desired 8^{th} magnitude sensitivity. In this case, the total update time would be 5 s, including a readout time of $\approx$ 1 s per frame, during which time we would expect the gyros to drift approximately 7$''$, or 1 CCD pixel. This is consistent with the $\approx$ 10$''$knowledge that we need for unique stellar identifications during the continual drift scan: Since the daytime star tracker must operate with pixel size $\sim$8$''$to minimize sky brightness background per pixel, star tracker (CCD) integration times must be $\lesssim$ 0.5sec to record a given star in $\lesssim$ 2 pixels. Thus aspect would be derived each 0.5sec to $\sim$10$''$, or some 30× better than required for a minimal Nyquist oversampling (2×) of the coded aperture telescope angular resolution of 10$'$.

Given this "overkill" on aspect (vs. pointing stability), it might be possible to simplify the gondola pointing and aspect system to be entirely GPS based. We have achieved (on our 1997, 2000 and 2001 balloon flights under our EXITE SR&T program in collaboration with MSFC) an aspect (azimuth only) of $\lesssim$ 5$'$. This could be improved probably to $\lesssim$ 3$'$ with wider GPS antenna spacing or the addition of several more GPS antennas. Gondola (and thus fixed-telescope) elevation can be determined to a comparable ($\lesssim$ 2$'$) accuracy with precision inclinometers (already flown).

3.4.3 Computer Communication and Control Systems

Two computer systems have been developed to handle gondola communications and control functions. The Housekeeping (HK) system monitors the current state of the gondola including temperatures, voltages, pressures, etc. It also handles communications to the ground and relays communications between other gondola systems through the on-board 10BaseT network hub. The Control (CTL) system, shown in Figure 6, monitors all rough aspect sensors and commands both azimuth and elevation motors to control detector pointing. Both the HK and CTL systems are low-cost, low-power PC/104 based commercial systems. A custom analog interface card is common to both systems as is a custom DC-DC board that converts battery bus voltages to useable system voltages. Both systems are packaged in sealed cylindrical vessels that are purged with dry nitrogen before launch. Both systems have fans to circulate the internal atmosphere and 40W heaters that can be used to regulate night cold cycles.

One important function of the HK system is to provide to all other gondola systems a time reference synchronized to UTC. The HK system updates its own system clock by monitoring the pulse per second output of a GPS receiver and the GPS time packet broadcast from the satellites. GPS time is converted to UTC and at intervals a time packet is broadcast over the 10BaseT network to all gondola systems. A TTL pulse then follows the broadcast to allow other systems to synchronize their clocks to the rising edge of the pulse. Timing to within ± 1 μsec of UTC is possible although individual system resolution may vary. Using this approach any

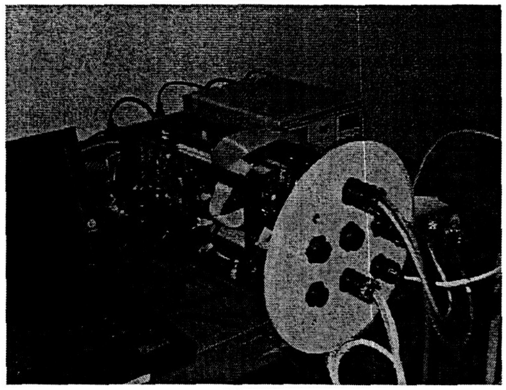

Figure 6: Gondola control computer removed from pressure vessel housing undergoing bench tests.

number of separate gondola systems can be time synched together.

All gondola systems, Housekeeping (HK), Control (CTL), and Aspect (ASP) are connected through the 10BaseT network. This method provides a high bandwidth gondola communication path for both data and command information. All command data is transmitted through NSBF equipment to the HK system. Each command data packet is parsed by the HK system to determine the packet destination and then routed through the network to the specified gondola or detector system.

Each gondola system transmits a time-tagged state-variable packet including voltages, pressures, currents, etc. to the HK system where it is buffered and transmitted to the ground at a rate of 4 kbs. The HK system monitors gondola structure, gondola system, and detector system temperatures as well as the ambient temperature and pressure. The CTL system sends data including gyro readings, shaft angle encoder readings, inclinometer, magnetometer, and GPS aspect information packaged with a 0.1 s resolution to the HK system where they are buffered and send to the ground. Time-tagged and compressed (background pixels suppressed) camera images are stored onboard the ASP system for post flight analysis while compressed images are routed to the HK system for transmission to the ground in real time. All HK packets sent to the ground are time tagged and appended with a 16-bit CRC word to verify data transmission integrity.

3.4.4 Science Data and Telemetry

We shall further develop the data handling and storage system for EXIST-LITE during this second year. The relatively high event rates ($\sim$0.3cts/cm^2-sec or $\sim$2000 cts/sec; cf. background measurements of Jenkins et al 2003) dictate that it is most efficient to bring down each event separately as its position (x,y), energy and time. At 50 bits per event, the total science telemetry required is 100kbs, which could be brought down in several high TM passes per day (via TDRSS?). Data would be stored on board to hard disk (as well as redundant backup) since the total data volume for a $\sim$100d ULDB flight is only $\sim$125Gb.

3.4.5 Power Requirements

The dominant power requirement is for the ASICs reading out the CZT array. However, with (only) 102,400 pixels [(800mm/2.5mm)^2] in the full 4-telescope array, and a conservative power consumption of 1mW/pixel (even for the lab prototype shown in Fig. 4), the total detector focal plane power is only $\sim$100W. Combined with shield power, onboard computers, and gondola systems, the total estimated power requirement is 350W (cf. Table 1), well within the capabilities of a four-fold solar panel array as depicted in Fig. 3.

3.4.6 LDB Precursor mission?

Finally, although this Study is directed towards a ULDB mission, we shall also consider the option of developing an initial version of the payload (possibly with fewer CZT modules per telescope) for an earlier LDB flight from Antarctica. We believe a half-cale payload could be built within ~3 years if additional funds were found (through the SR&T program). A ~10d LDB flight from Antarctica would allow an impressive wide-field survey sensitivity (~5mCrab, allowing also for the higher particle backgrounds at this high geomagnetic latitude) within 20° of the south celestial polar cap (i.e. DEC $\lesssim$ -70°) since this sky is *continously* observed by at least partial detector area for the full mission duration. This would allow an impressively sensitive survey of the LMC/SMC. We shall study this intermediate LDB concept (EXIST-*LITE* as a stepping-stone to the full EXIST-LITE and ultimately EXIST mission.

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